Medium- and Heavy-Duty Vehicle Choice Modeling and Applied Analysis

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National Renewable Energy Laboratory
June 22, 2021

DOE Vehicle Technologies Program
2021 Annual Merit Review and Peer Evaluation Meeting

Project ID # VAN034

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

- Project start date: 10/01/2019
- Project end date: 9/30/2022
- Percent complete: 45%

Barriers

- Indicators and methodology for evaluating benefits
- Complexity of freight transportation system
- Relating component-level technologies to national-level benefits
- Reliable and current medium- and heavy-duty (MDHD) market and operational data with sufficient detail/granularity

Budget

- Total project funding: $900,000
  - DOE share: 100%
- Funding for FY 2021: $300,000

Partners/Collaborators

- NREL: Alicia Birky and Aaron Brooker, co-PIs; Lauren Sittler, Chen Zhang, Jason Lustbader, Arthur Yip, Chad Hunter, Evan Reznicek
- DOE cross office: Vehicle Technologies Office (VTO), Hydrogen and Fuel Cell Technologies Office (HFTO), Bioenergy Technologies Office (BETO)
- 21st Century Truck Partnership (21CTP)

Relevance to VTO Analysis Program Goals

Analysis Program Goals	Project Relevance
Provide critical information and analyses to ***inform VTO research portfolio planning*** through technology-, economic-, and interdisciplinary-based analysis, including ***target-setting*** and ***program benefit estimation***.	• Legacy and Automotive Deployment Options Projection Tool (ADOPT) MDHD modeling frameworks ***support program benefits estimation***. • Integrated Future Automotive Systems Technology Simulator (FASTSim)-ADOPT framework enables ***simultaneous exploration of technical targets and program benefits***.

Provide essential vehicle ***modeling and simulation*** and applied analysis using unique ***capabilities, tools, and expertise*** resident in the National Laboratories.
• Creation, maintenance, and utilization of vehicle and system models to explore energy impacts.
• ***Integration of multiple models*** to yield ***useful findings***.
	• Both legacy and ADOPT frameworks ***leverage FASTSim capabilities and MDHD models developed for various activities across VTO and HFTO***.
	• Both frameworks integrate simulation results, market adoption, and stock modeling.
	  • Legacy – manually
	  • ADOPT – internally

Provide a holistic view of the transportation system and identify ***opportunities for advanced vehicle technologies to*** strengthen national security, increase reliability, and ***reduce costs***.	• Benefits analysis translates VTO targets into ***projections of in-use energy and emissions savings and expenditures*** on vehicles and fuel. • Legacy payback methodology reflects adoption of ***cost-effective solutions that reduce lifetime transportation and truck freight movement costs***.

MDHD Scope: Weight Classes 4–8 (Gross Vehicle Weight Rating [GVWR] >14,000 lbs), potentially Class 3 (10,001–14,000 lbs).

Objectives

Main Objective: Provide critical analysis, tools, and information to prioritize and inform VTO research portfolio planning; explore energy-specific vehicle and transportation system advancements to inform VTO's early-stage research; and offer analytical direction for potential and future research investments

Specific Project Goals to Meet Objective

- Provide continuity in benefits analysis support and develop cutting edge capabilities/approaches
- Develop ADOPT MDHD capabilities to ***enable light-duty (LD) and MDHD analysis in a consistent, streamlined framework***
- Maintain and enhance legacy models (TRUCK + HDStock) and analysis approach during MDHD ADOPT development
- Analyze transportation decarbonization scenarios to explore transition pathways to net zero emissions

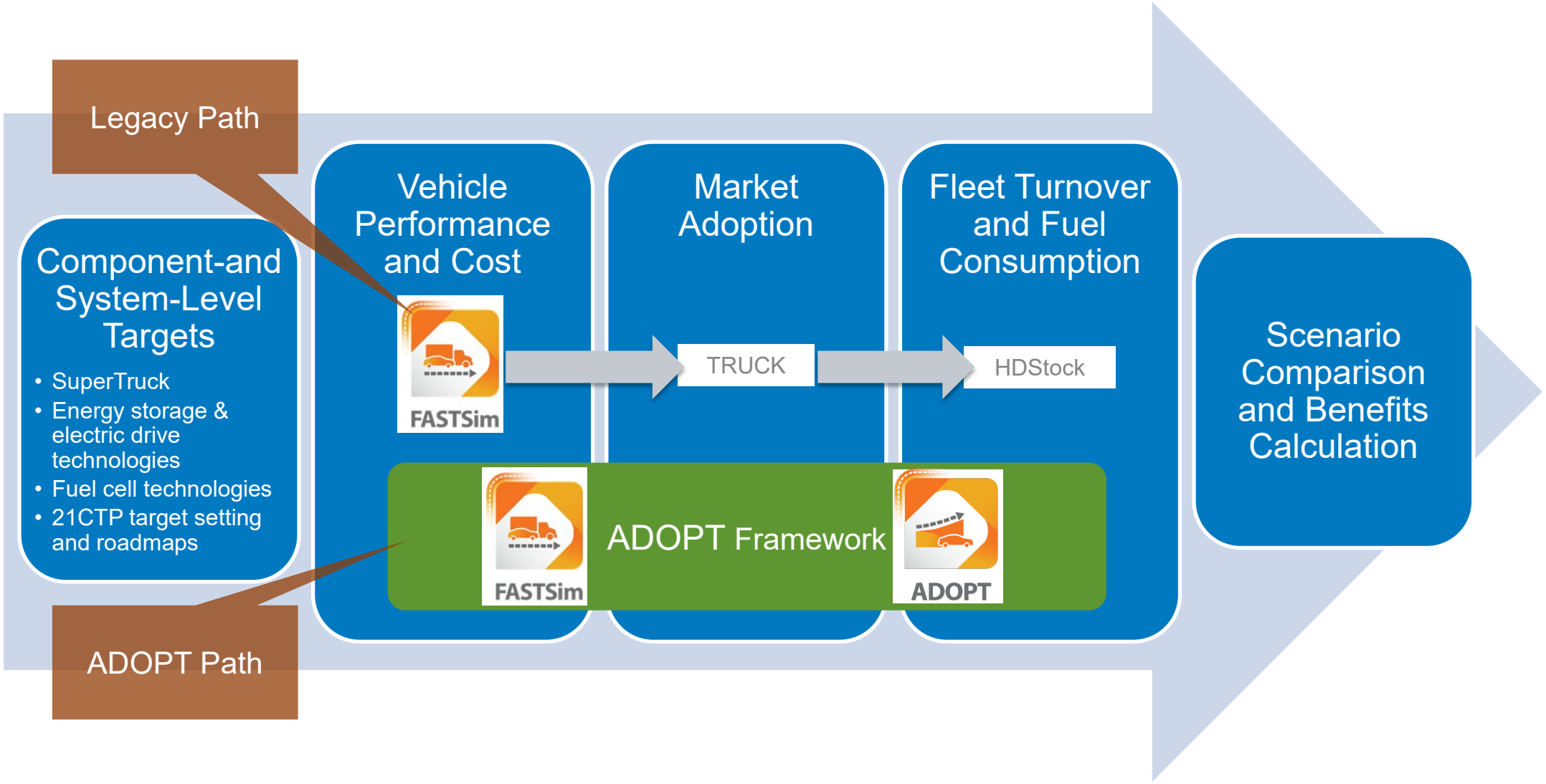
Year 2 Objectives

- ADOPT
  - Refine validation for Class 8 tractors using updated vehicle sales data
  - Expand coverage to other classes/segments
- Legacy TRUCK choice model
  - Enhance model capabilities to enable analysis of a wider range of technologies for evolving VTO, HFTO, and BETO portfolio
- Complete annual MDHD benefits analysis
  - Capture latest understanding of future electrification technology performance and cost in context of DOE's goals
  - Develop and analyze decarbonization scenarios to inform DOE strategy
  - Use ADOPT and TRUCK in parallel

Milestones

Date Due	Description	Status
September 2020	Complete TRUCK model documentation updates.	Complete
September 2020	Deliver MDHD Benefits Analysis Report for DOE review.	Complete
September 2020	Go/No-Go: Based on progress with ADOPT MDHD development, determine whether to phase out use of TRUCK in FY 2021, continue with a parallel MDHD choice model approach, or redouble efforts for further needed TRUCK revisions and enhancements.	Go
December 2020	Summarize plan for updated handling of No Program scenario with legacy TRUCK modeling approach.	Complete
March 2021	Establish priorities for the re-visioned 2021 LD and MD/HD Benefits Analysis and associated plan for eliciting future technology progress assumptions from DOE Technology Managers.	Complete
June 2021	Report on updated MD/HD ADOPT capabilities – provide a presentation and/or draft technical paper describing MD/HD ADOPT updates and enhancements.	On Track
December 2021	Summarize updates and enhancements implemented in the TRUCK model	On Track
December 2021	Go/No-Go: Based on progress with MD/HD ADOPT development and revisions/enhancements to the legacy TRUCK approach, determine whether to continue with a parallel MD/HD choice model approach or collapse to a single approach.	

MDHD Benefits Analysis Approach Overview: Translating Component and System-Level Targets into In-Use Energy Savings Benefits



Approach: ADOPT-HD (Initial focus on Class 8 tractors)

Process

1. Scenarios start with all existing Class 8 tractor options

- Captures diversity of performance characteristics & pricing

ADOPT

2. New vehicles introduced to the market based on best-selling models

- Trade-offs made in vehicle attributes based on the relative value to consumers

3. Sales estimates are used for future vehicle evolution

- Process iterates every year through 2050
- Component sizing is optimized using the integrated powertrain model FASTSim

FASTSim

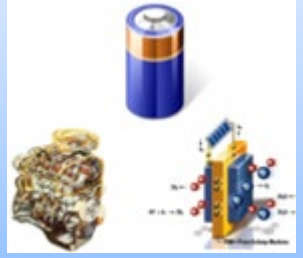
4. Sales placed into a stock model to estimate total fleet GHG emissions and petroleum consumption

ADOPT goes beyond cost/payback framework to capture performance advantages advertised by manufacturers:

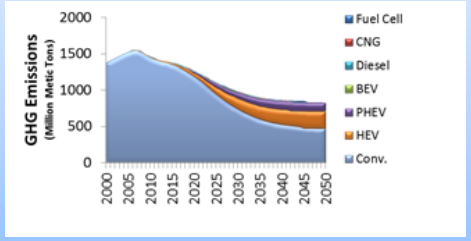
- Vehicle attributes include acceleration time; faster acceleration can provide safety benefits at lights and merge ramps

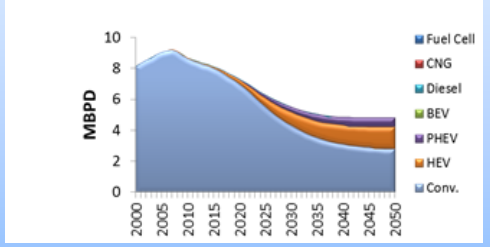
Overall Result

Technical Targets



Vehicle Emissions and Energy Consumption





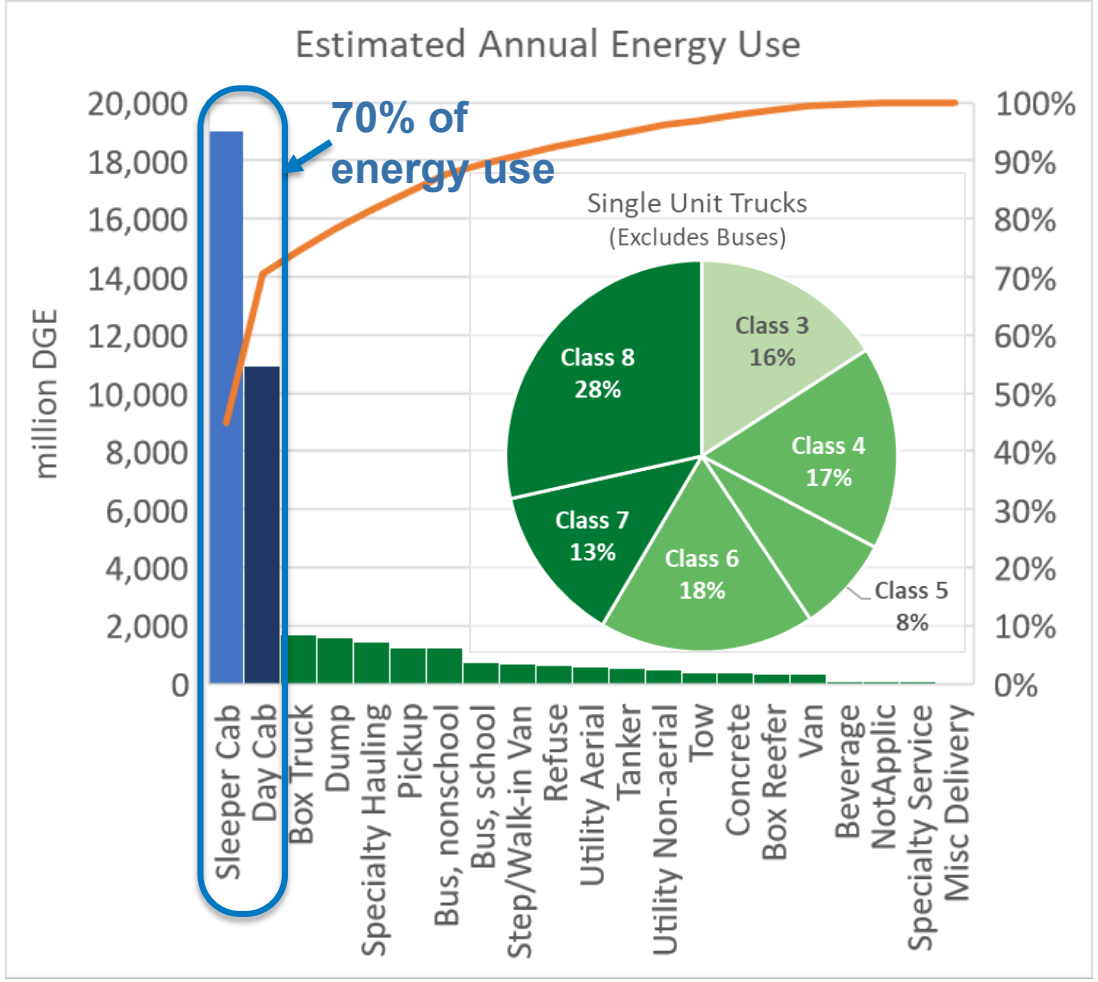
Approach: Planned expansion to ADOPT-MDHD

Update ADOPT for Class 8 tractors

- Highest fuel user – biggest impact
- Framework updates
  - Change from income-based preferences to VMT-based preferences
  - Acceleration (increase max time from 10 s to 60 s)
  - Add missing potential powertrains
  - Add HD drive cycle leveraging NREL target-setting efforts
- Update with HD inputs
- Review and revise

Go/No-Go

Complete updates for other MDHD classes



Source: Analysis by NREL (2020) of 2013 IHS Polk registrations, 2017 National Transit Data Base, 2002 Vehicle Inventory and Use Survey (VIUS), and various other data sources.

VMT = vehicle miles travelled DGE = Diesel gallon equivalent

Approach: TRUCK Market Adoption Model Overview and Goals

Annual Energy Outlook (AEO) Fuel Prices

Vehicle Performance & Cost

FASTSim

TRUCK

- Separate model for each market segment
  - Class 7&8 Sleeper Tractors
  - Class 7&8 Day Cab Tractors
  - Class 7&8 Vocational Trucks
  - Class 4-6 Vocational Trucks
- Base + 5 alternative vehicles using any fuel
  - R version has no limit on number of alternatives
- Adoption based on payback
  - 20,000-mile cohorts
  - Central, non-central distributions
  - Survey on acceptable payback
- Adjustments
  - Technology phase-in
  - Incremental cost as % of base cost
  - Fuel availability

Outputs
(Inputs to HDStock)

- Sales shares
- Sales fleet mpg
- PHEV utility factor

- Investigate alternative algorithms for competition of multiple technology options leveraging new flexible modeling platform
- Refine capabilities for expanded technology portfolio, including fuel availability response
- Document methodology and capabilities

ADOPT MDHD Technical Accomplishments and Progress

Captured HD Consumer Preferences

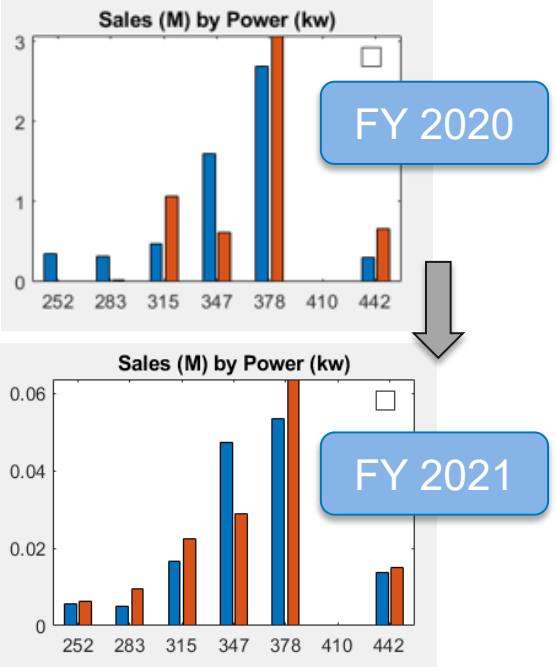
- **Coefficients specify the relative value of each vehicle attribute.**
- **Updates were made to reflect HD vehicles and consumers.**
  - Consumer characterization by VMT (LD is income-based)
  - Adjusted the fuel cost discount rates by consumer type.
  - Increased 0-60 mph acceleration time and lower value to consumers.
  - Adjusted interior volume coefficient.
  - Adjusted the penalties for battery electric vehicle (BEV) range.

Integrated ADOPT HD with LD

- **Merged the code, data, and settings into the main branch of ADOPT.**
  - Datasets for the HD sector, including sales, attributes, duty cycles, engine efficiency.
  - HD preference settings
  - Model coefficient to specify vehicle class and adjust range preference
  - Logic to recognize HD vehicle creation, size vehicle components by weight, and turn off LD light-weighting.
- **HD and LD scenarios can now be run from the same user interface.**

Improved Validation of Results

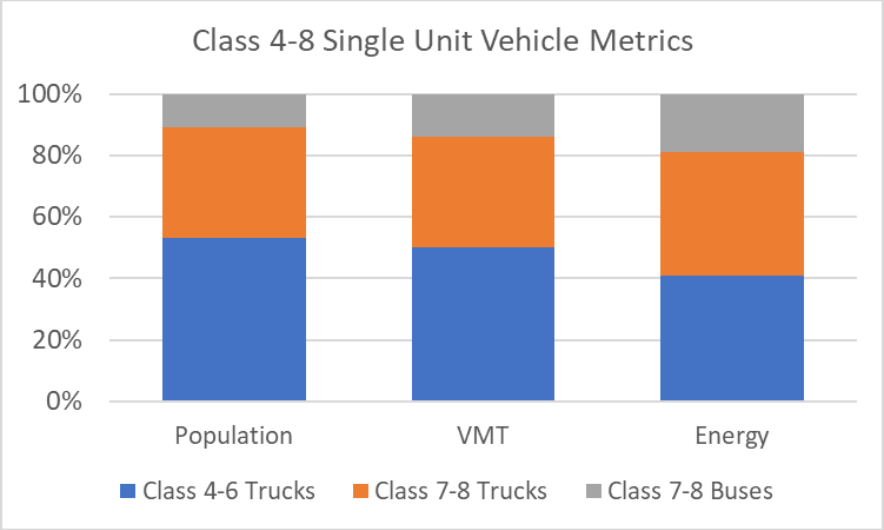
- **Optimized attribute coefficients to better match historical sales data.**



- Truck attributes and preferences considered in choice modeling
- Consistent LD and HD benefits analysis methodology
- Results validated to sales by engine power

ADOPT MDHD Technical Accomplishments and Progress: Expansion to Additional Market Segments

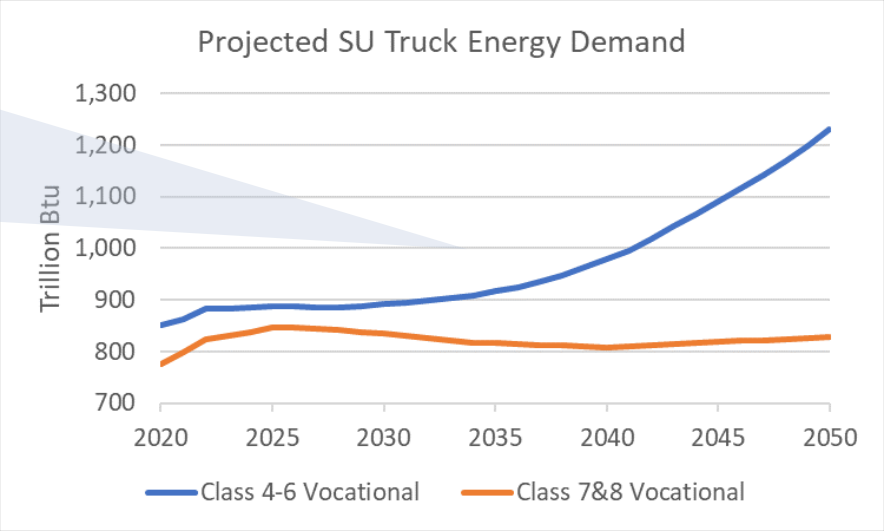
- Assessed next MDHD segment beyond tractor-trailers to model using ADOPT
- Proposed: Class 4-6 single-unit (SU) trucks
  - Accounts for just over half of class 4-8 SU truck energy
  - High growth segment
  - High potential for ZEV adoption
  - Begin with pickup and delivery duty cycle



Source: Analysis by NREL of 2013 IHS Polk registrations, 2017 National Transit Data Base, 2002 VIUS, and other data.

✓ Addresses priorities for benefits analysis
- Aggregate energy use
- Sales and future growth
- Segments where operations and fueling needs indicate possible alternative-fuel beachhead

✓ Considers key factors and constraints including:
- Duty cycle consistency across segment
- Buyer behavior (preference vs. job requirements)
- Data availability and detail



Source: HDStock calibrated to AEO2021 projection.

TRUCK Technical Accomplishments and Progress: Fuel Availability

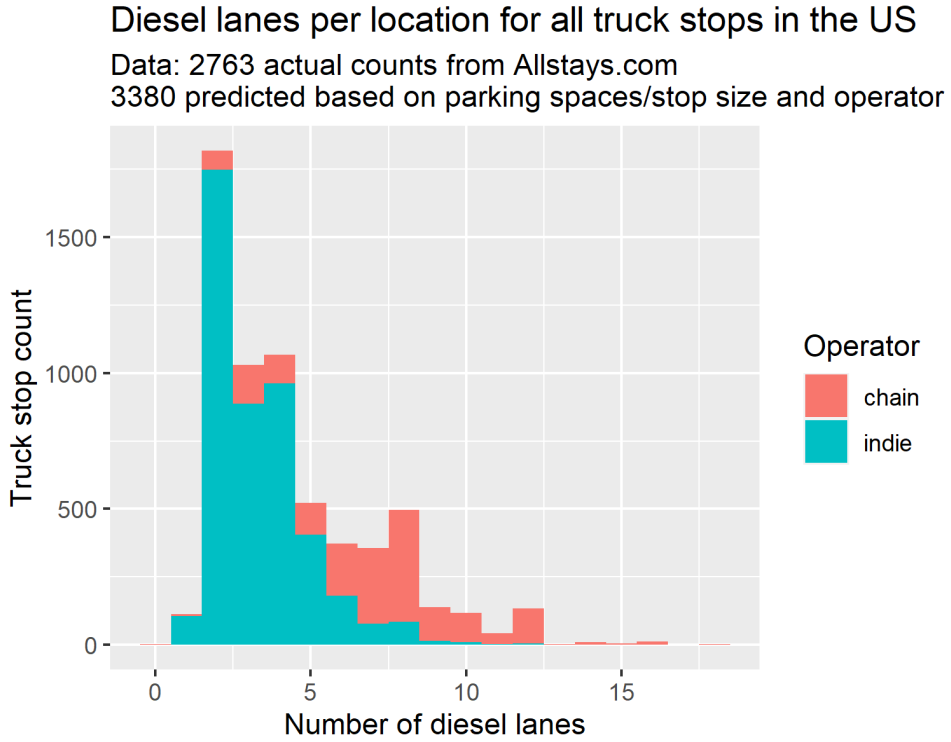
Estimation of Baseline Fuel Availability from Truck Stops and Diesel Lanes

- Truck stop data obtained to quantify baseline diesel fuel availability for tractor-trailers
  - Parking space counts used to estimate missing lane counts
  - Diesel lane counts converted to maximum throughput capacity in terms of maximum power for comparison to electric charging

Highlights

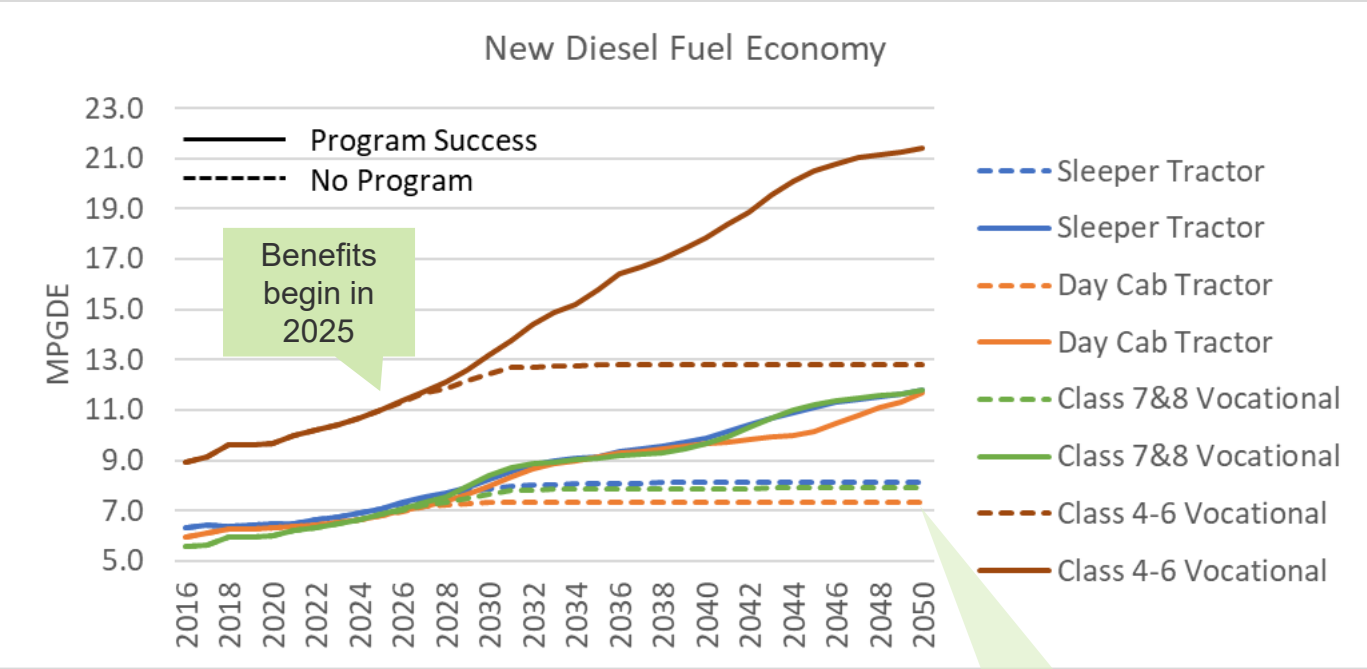
- Largest truck stops have 18 lanes, capable of delivering fuel at ≈2 GW
- Totals for the US from this mined data set:
  - 6,231 truck stops, 27,204 lanes
  - ≈2,700 GW of maximum energy flow at 100% utilization
    - Without accounting for use profiles or time for truck to pull in/out
- Comparison point: Total public EVSE for LDVs in the US today ≈ 2 GW

Source: Google Maps API



Benefits Analysis Technical Accomplishments: FY 2020 Analysis Results

Adoption of Advanced Diesels and Diesel Hybrids Increases New Diesel Fleet Fuel Economy



No Program Case: AEO Reference Case sales fleet diesel tractor fuel economy adjusted to remove impact of VTO-funded component technologies

- Sleeper tractors just meet Phase 2 fuel consumption standards; no adjustment
- Main technologies removed: highest tier aerodynamics, turbo-compounding
- No hybrid adoption in the AEO Reference or No Program cases

Hybridization (non-plug-in) is included in diesel fuel economy

By 2050, Stock Fuel Economy Relative to No Program:

45% Sleeper Cab
59% Day Cab
48% Class 8 Vocational
58% Class 4-6 Vocational

49% All Class 3-8 Diesel

Program Case Hybrid Share of Diesel in 2050

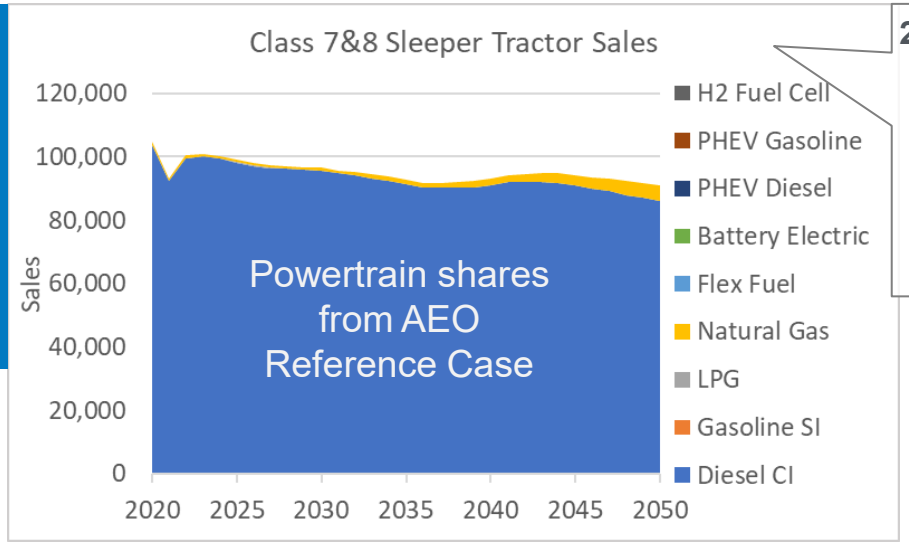
Class	HEV share
Sleeper Tractor	48%
Day Cab Tractor	41%
Class 7&8 Vocational	52%
Class 4-6 Vocational	51%

Benefits Analysis Technical Accomplishments: FY 2020 Analysis Results

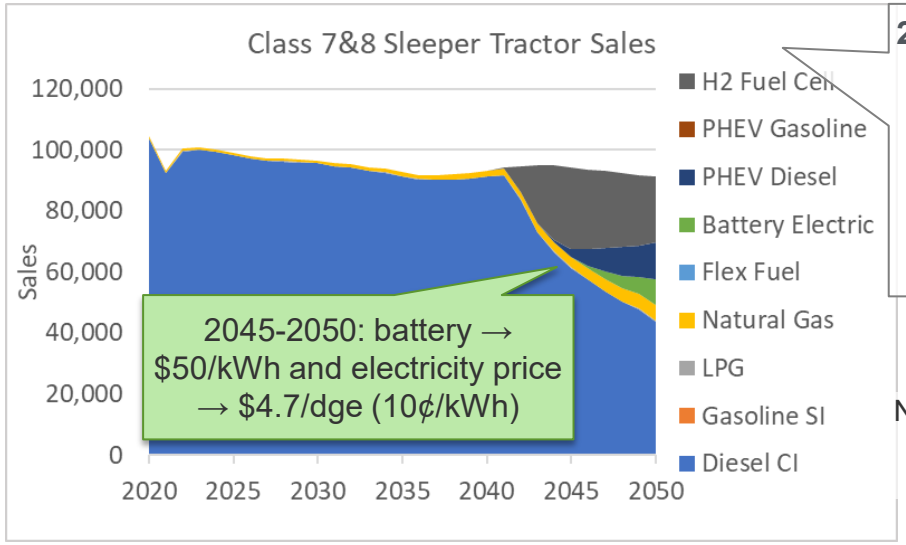
Tractor Sales of Electrified Powertrains Expand after ~2040

No Program → Program Success

Sleeper Tractors



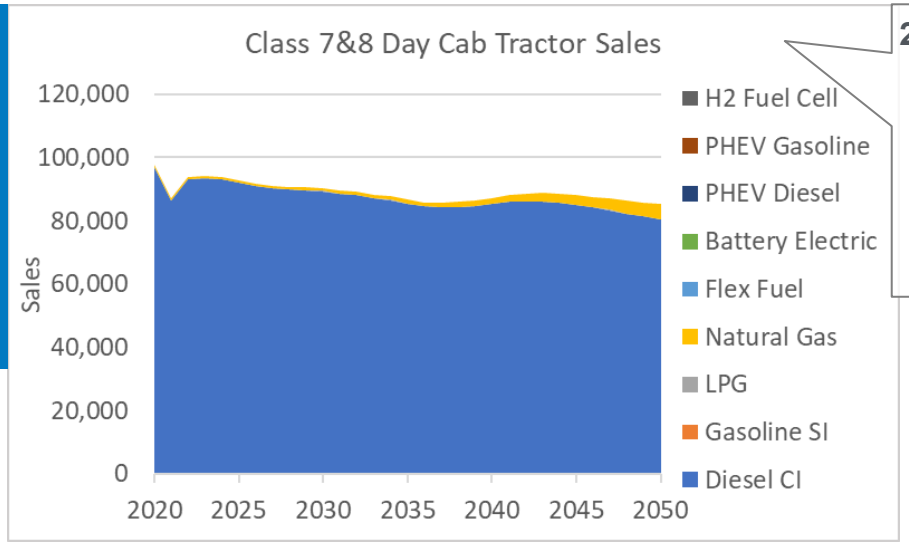
2050 Shares:
0% FCEV
0% PHEV-D
0% BEV
6% CNG
94% Diesel



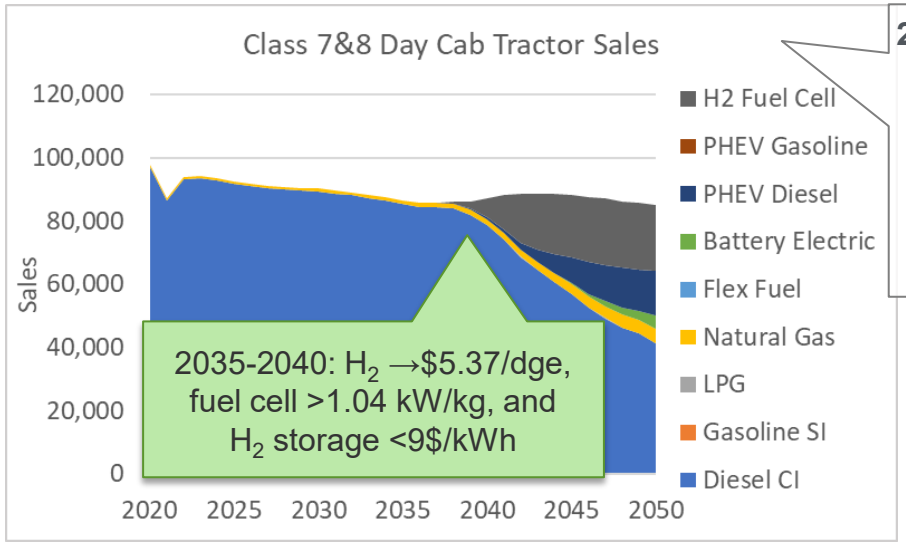
2050 Shares:
24% FCEV
13% PHEV-D
9% BEV
6% CNG
48% Diesel

NG & LPG shares from AEO Reference Case

Day Cab Tractors



2050 Shares:
0% FCEV
0% PHEV-D
0% BEV
6% CNG
94% Diesel



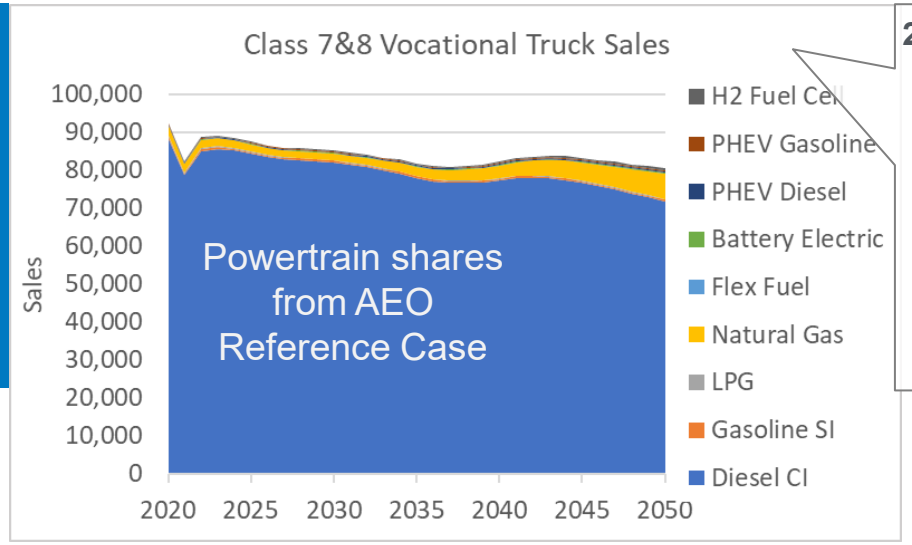
2050 Shares:
24% FCEV
17% PHEV-D
5% BEV
6% CNG
48% Diesel

Benefits Analysis Technical Accomplishments: FY 2020 Analysis Results

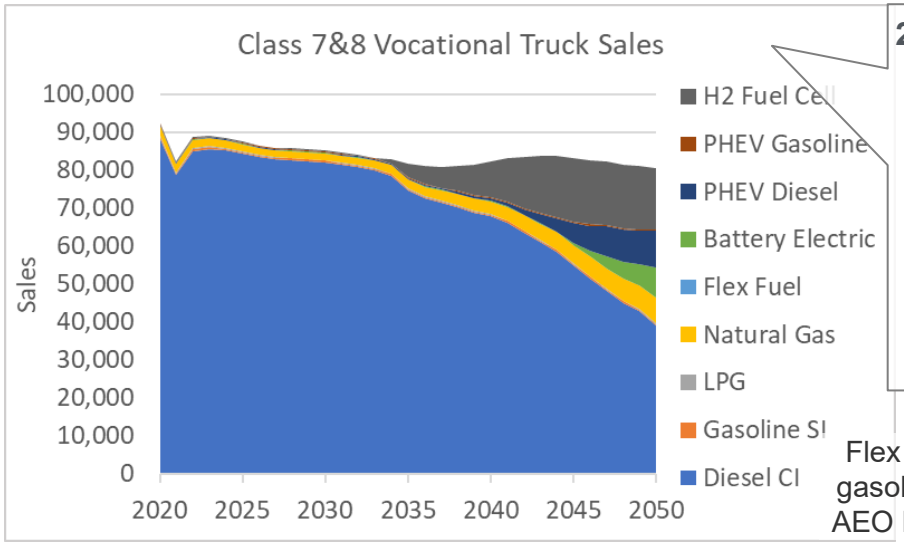
Vocational Truck Sales of Electrified Powertrains Expand after ~2030

No Program → Program Success

Class 7&8 Vocational



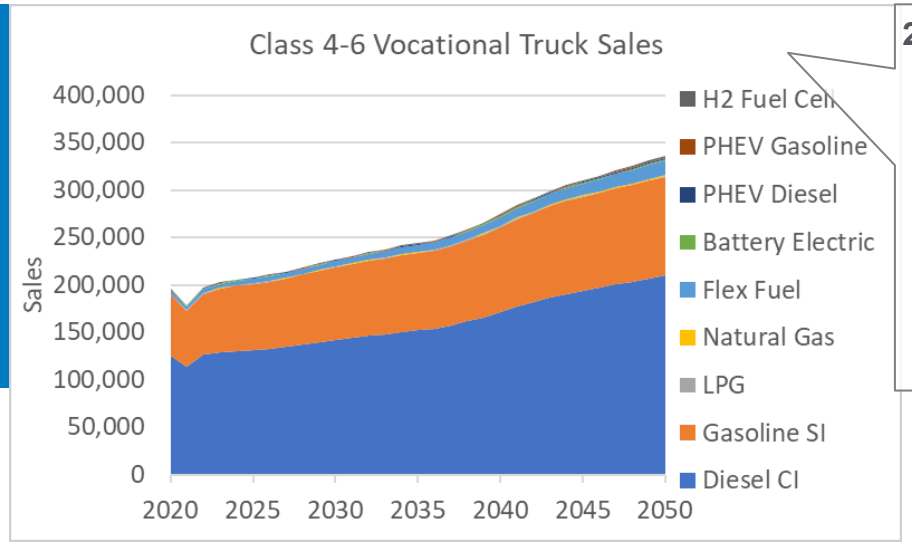
2050 Shares:
- <1% FCEV
- <1% PHEV-G
- <1% PHEV-D
- <1% BEV
- 8% CNG
- <1% Gasoline
- 89% Diesel



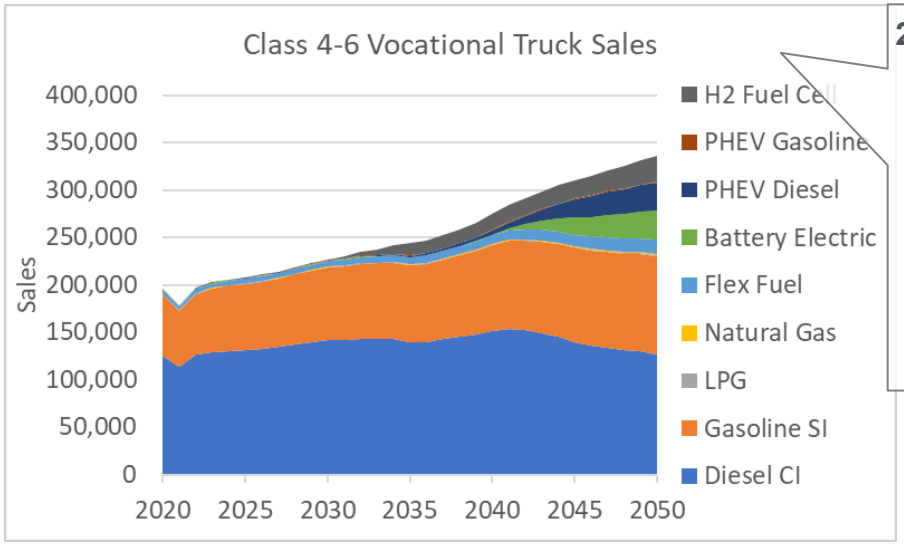
2050 Shares:
- 20% FCEV
- <1% PHEV-G
- 12% PHEV-D
- 10% BEV
- 8% CNG
- <1% Gasoline
- 48% Diesel

Flex fuel, NG, LPG, gasoline shares from AEO Reference Case

Class 4-6 Vocational



2050 Shares:
- <1% FCEV
- <1% PHEV-G
- <1% PHEV-D
- <1% BEV
- <1% CNG
- 31% Gasoline
- 62% Diesel



2050 Shares:
- 8% FCEV
- <1% PHEV-G
- 9% PHEV-D
- 9% BEV
- <1% CNG
- 31% Gasoline
- 38% Diesel

Benefits Analysis Technical Accomplishments: FY 2020 Analysis Results

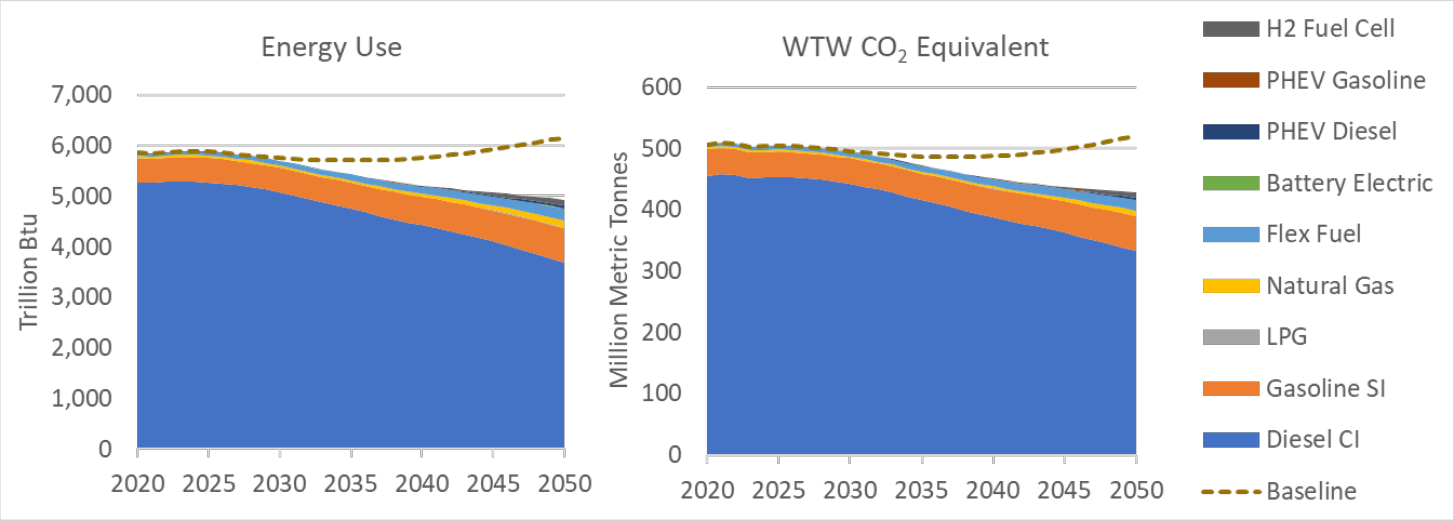
Higher Diesel Efficiency and Electrified Powertrains Reduce Diesel Consumption, GHG Emissions, and Net Expenditures

Annual in 2050:

- 28% Diesel
- 20% Energy*
- 21% Class 4-8 CO_2e
- 18% All MDHD CO_2e

* Tank to wheels

Well to wheels



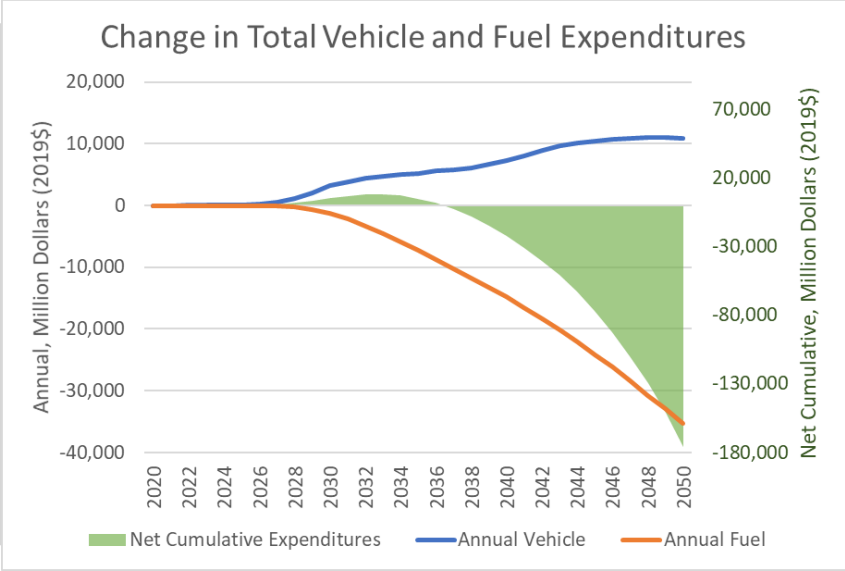
Note: Scenario totals include class 3 for which no change / benefits are analyzed.

Cumulative by 2050:

- 13 quads diesel (7.4%)
- 835 Mt CO_2e (5.1%)

Net Expenditures in 2050:

- $24 billion annually
- $176 billion cumulative



Technology adoption based on payback results in net vehicle-level savings in less than 4 years.
Net in-use fleet-level savings begin in 2037.

Benefits Analysis Technical Accomplishments and Progress: FY2021 Methodology Improvements

- Model "No Program Case" vehicles in FASTSim and estimate market shares
  - Covered powertrains: Diesel (including HEV), BEV, PHEV diesel, FCEV
  - Gasoline, flex fuel, natural gas, and propane vehicle performance and sales shares maintained at AEO Reference Case levels

  Status: Gathering input assumptions from DOE TMs

- Expand FASTSim vehicle models to include more subclasses and configurations

  Status: Base engine load curves have been developed; base model validated against test data and EPA emissions compliance model.

✓ More consistent with light duty analysis
✓ Solves issues with diesel component and electrification technology progress under no-program funding assumptions
✓ Balances priorities in powertrain technologies with resource constraints
- Targets primary DOE research areas
- Small CNG market (<4% in class 7&8)
- Stable class 4-6 gasoline market (25% of class 4-6)

Class	FY 2020 Models	FY 2021 Models
Class 8 Sleeper Tractors	Class 8 High Roof Sleeper	Class 8 High Roof Sleeper Class 8 Mid Roof Sleeper Class 8 Low Roof Sleeper
Class 7&8 Day Cab Tractors	Class 8 High Roof Day Cab	Class 8 High Roof Day Cab Class 8 Mid Roof Day Cab Class 8 Low Roof Day Cab
Class 7&8 Vocational Trucks	Class 8 Box Truck	Class 8 Box Truck Class 7 Box Truck
Class 4-6 Vocational Trucks	Class 6 Box Truck	Class 6 Box Truck Class 5 Box Truck Class 4 Step Van

Responses to Previous Year Reviewers' Comments

- This project was not reviewed in the previous year.

Collaboration and Coordination

- Establishing appropriate modeling inputs requires coordination across DOE:
  - VTO program managers with MDHD portfolio activities
    - SuperTruck
    - Electric Drive Technologies
    - Energy Storage
  - HFTO MDHD vehicle targets and analysis
  - BETO
- Leveraging NREL efforts across VTO, HFTO, BETO, and work for others (where possible)
  - Expertise, knowledge, model development, and data
  - Outcomes from 1 MW+ charging and depot charging projects
- Project benefits from collaboration with industry through 21st Century Truck Partnership
  - NREL team members participate in monthly tech team and working group meetings and actively support analyses
  - NREL support to electrification infrastructure working group
  - Presentation of assumptions, methodology, and results for review and feedback

Remaining Challenges and Barriers

- Lack of data for fuel availability response validation
- Low availability of market data with sufficient detail for MDHD techno-economic modeling
  - Insufficient body detail and vehicle configuration in registration data, especially non-tractors
  - Outdated VMT and refueling location type (VIUS)
  - Lack of public sources for transaction prices; limited sources for list prices and inability to calculate sales-weighted averages
- Finding pathways to MDHD decarbonization
  - Need for cost-effective solutions
    - Cost-driven, risk-averse fleet customer
    - Potential economic impact of higher freight costs
  - Stock turnover, low number of existing options, low production volumes and capacity, and supply chain competition point to a slower transition compared to LD

Future Work

Modeling

Remainder of FY 2021

- Obtain expert feedback on fuel availability response methodology and parameterization
  - Leverage National Commercial Vehicle Data Framework data acquisitions and analysis for 21 CTP
- Present updated MD/HD ADOPT capabilities to DOE.
- Summarize updates and enhancements implemented in the TRUCK model
- Present ADOPT capabilities and expansion plan to VTO for Go/No-Go decision

FY 2022

- Depending on Go/No-Go decision, complete expansion of ADOPT to selected market segments/vehicle types

Benefits Analysis

Remainder of FY 2021

- Complete elicitation of benefits analysis input assumption from DOE technology managers
- Finalize decarbonization scenario analysis
  - Analyze how VTO, HFTO, and BETO technologies can help achieve transportation decarbonization goals
  - Assess technology development impacts under range of economic and policy conditions contexts
  - Assess sensitivity to key assumptions and timing
  - Present results to DOE

FY 2022

- Depending on Go/No-Go decision, analyze decarbonization scenarios in ADOPT
- Work with DOE to update and expand analysis

Any proposed future work is subject to change based on funding levels

Summary

Relevance	❑ MDHD benefits analysis provides critical information to inform VTO research portfolio planning. This is crucial as DOE sets goals to decarbonize the transportation system.
Milestones	❑ FY 2020 milestones were met ❑ Efforts are on track to meet FY 2021 milestones for ADOPT modeling and re-visioned benefits analysis.
Approach	❑ NREL has a sound approach that maintains continuity of benefits analysis support while developing enhanced and new capabilities.
Accomplishments	❑ ADOPT MDHD model quality testing is progressing well ❑ Completed and documented FY 2020 Analysis ❑ Additional FASTSim vehicle models have been developed and validated ❑ TRUCK model refactoring in FY 2020 will accommodate expanded scenario analysis for FY 2021-2022
Coordination	❑ The project team is coordinating with VTO, HFTO, BETO, and 21 CTP and is leveraging work within NREL that cuts across DOE-funded projects.
Remaining Challenges	❑ The MDHD sector suffers from serious data availability issues. NREL is working with DOE and external partners to mitigate these issues.
Future Work	❑ The team has a research plan to achieve remaining objectives for this fiscal year, address challenges, and meet VTO goals in future years.

Any proposed future work is subject to change based on funding levels

Thank You

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NREL/PR-5400-76740

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL
Transforming ENERGY

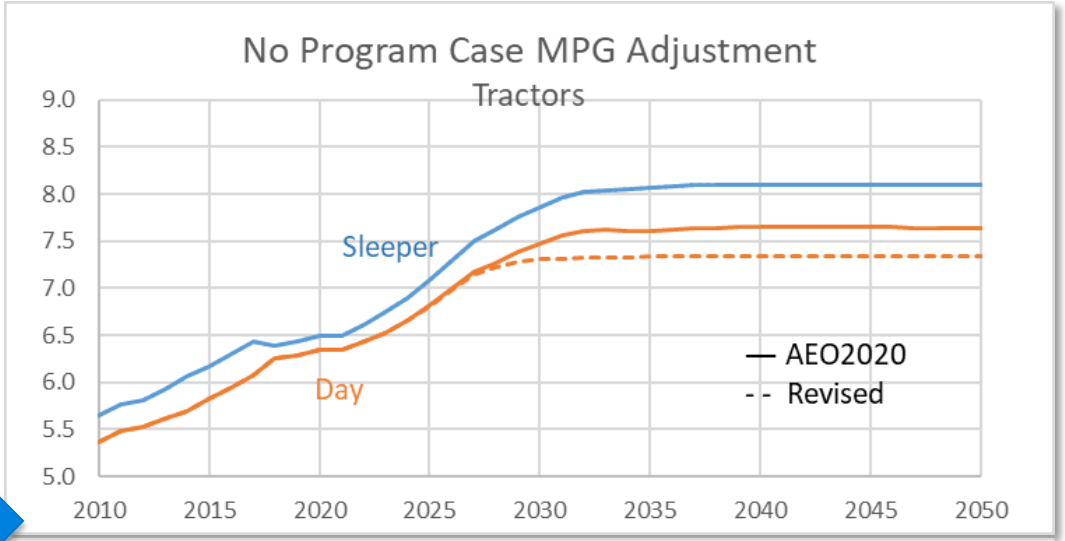
Technical Back-Up Slides

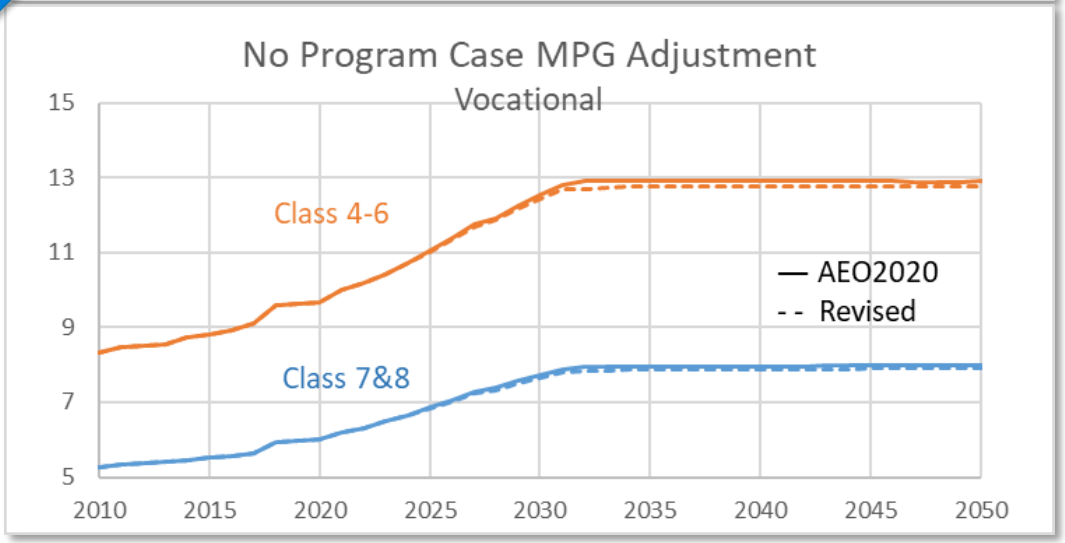
FY 2020 No Program Case Results

Diesel Technologies removed in 2050

	2050 share	fuel consumption reduction at this share		
Sleeper Cab		***low roof***	***mid roof***	***high roof***
No adjustments made to sleepers: AEO Reference Case was just at the Phase 2 Fuel consumption standard				
Day Cab, class 7		***low roof***	***mid roof***	***high roof***
Aero Bin 6	30%	0%	0%	3%
Aero Bin 7	18%	0%	0%	2%
Turbo compound with clutch	8%	<1%	<1%	<1%
Waste heat recovery	<1%	<<1%	<<1%	<<1%
Combustion/FI/Control, phase 2 pkg	100%	1%	1%	1%
Day Cab, class 8		***low roof***	***mid roof***	***high roof***
Aero Bin 6	30%	0%	0%	3%
Aero Bin 7	18%	0%	0%	2%
Turbo compound with clutch	8%	<1%	<1%	<1%
Waste heat recovery	<1%	<<1%	<<1%	<<1%
Combustion/FI/Control, phase 2 pkg	100%	1%	1%	1%

	2050 share	fuel consumption reduction at this share		
Class 4-6 vocational		***class 4***	***class 5***	***class 6***
Model based control	50%	1%	1%	1%
Class 7-8 vocational		***class 7***	***class 8***	
Model based control	50%	1%	1%	

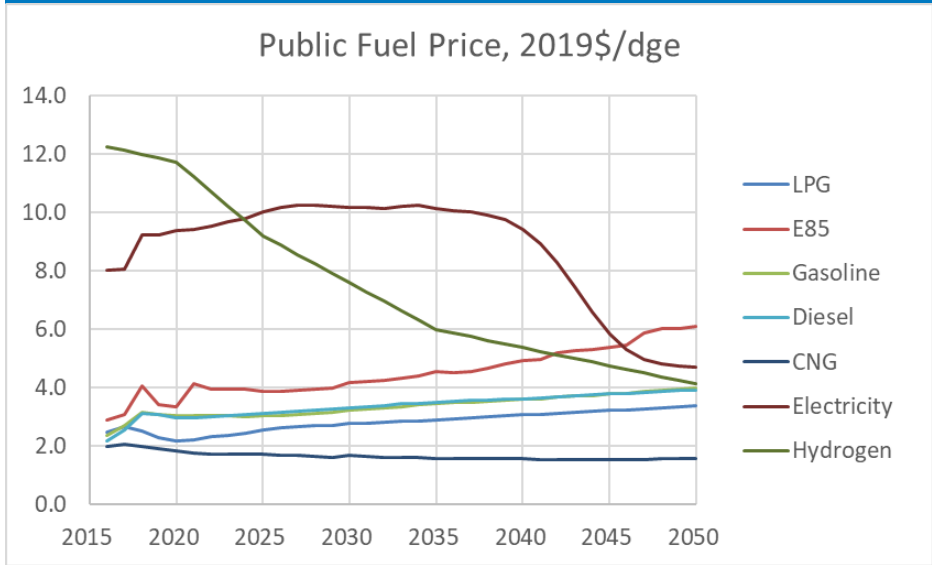


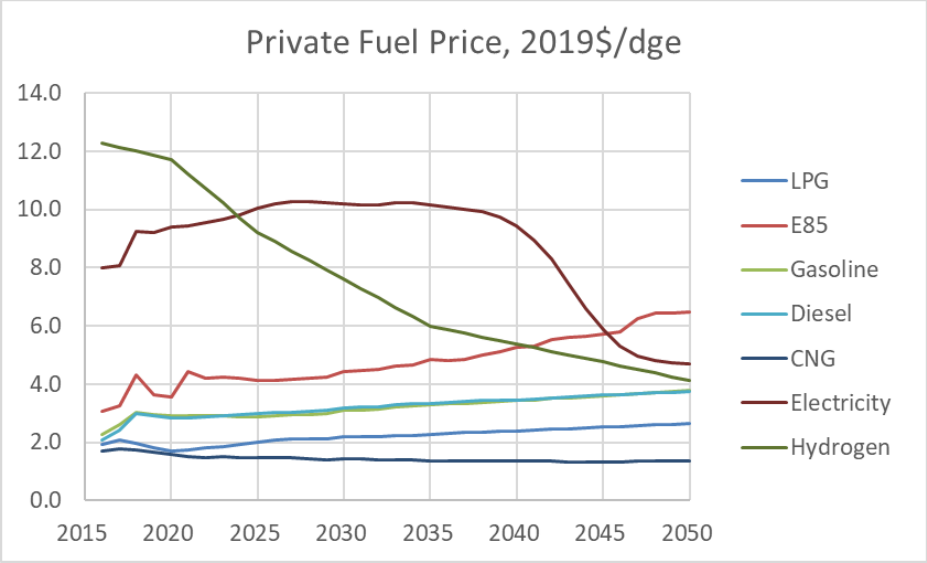


No Program Case retains minor shares of AFVs from AEO Reference Case:

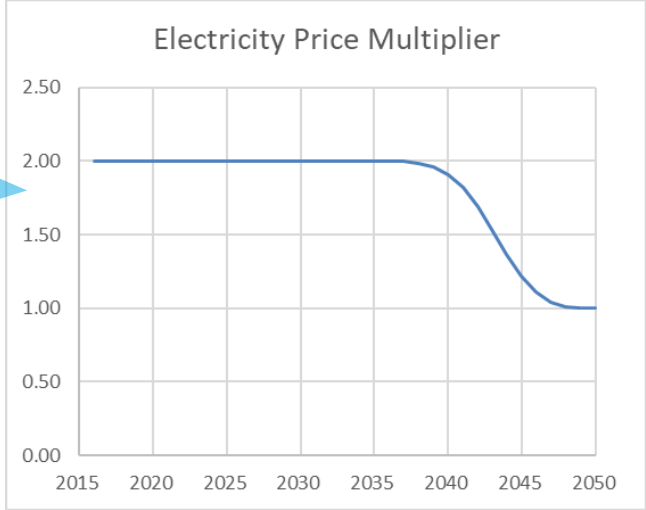
- Mostly CNG
- <1% electrified powertrains in Class 4-8

Fuel Prices from AEO 2020 Reference Case

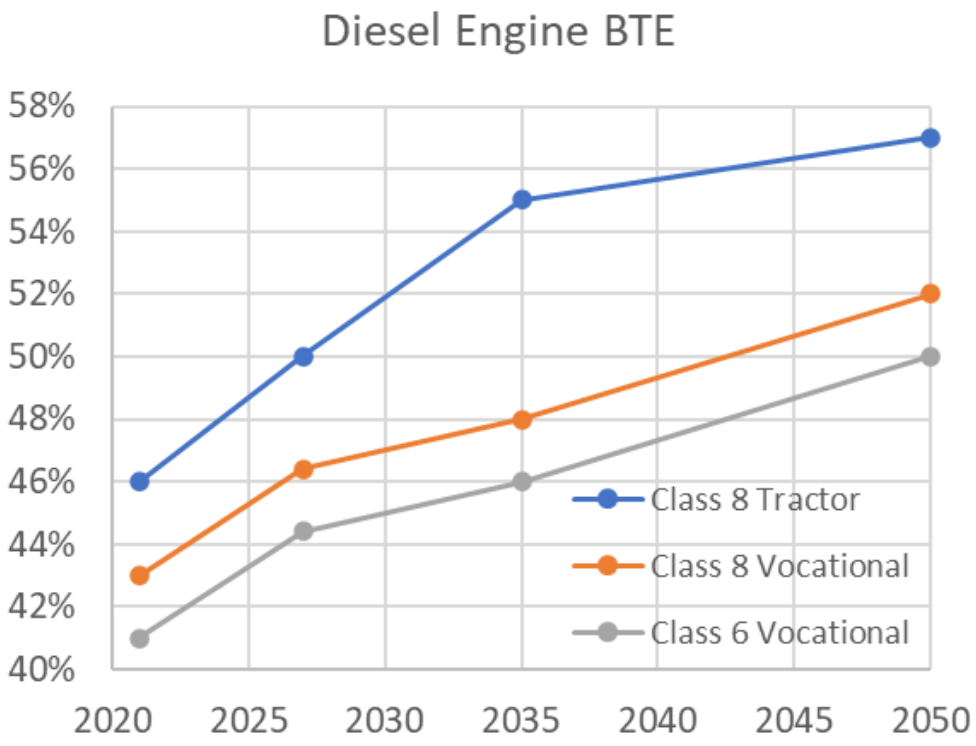


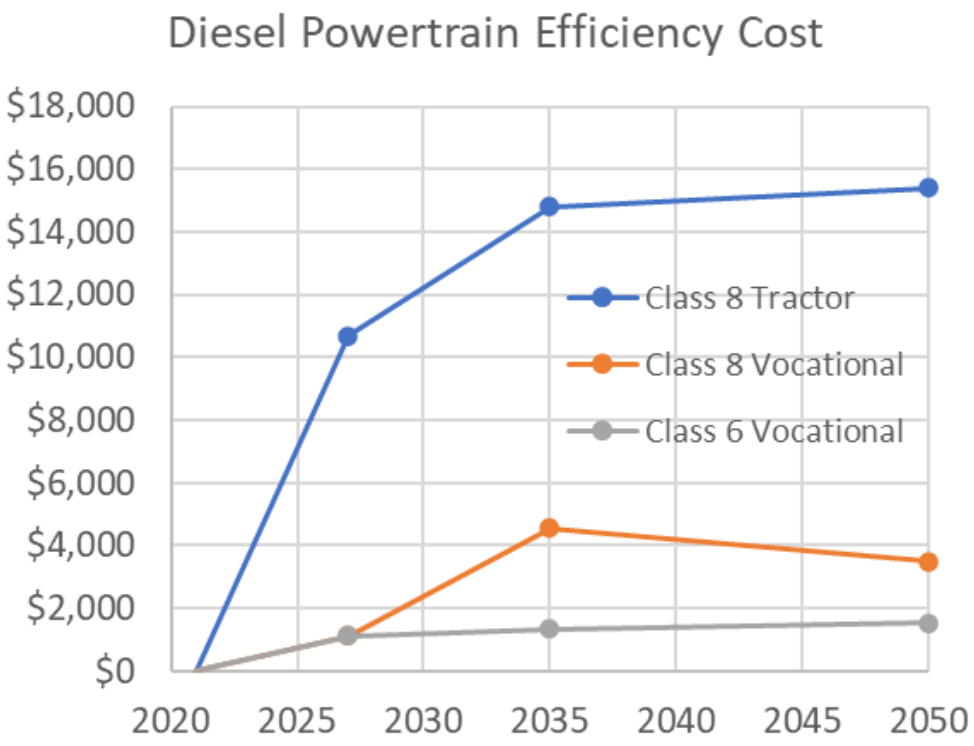


Multiplier applied to AEO electricity price to transportation to account for recapture of infrastructure investment



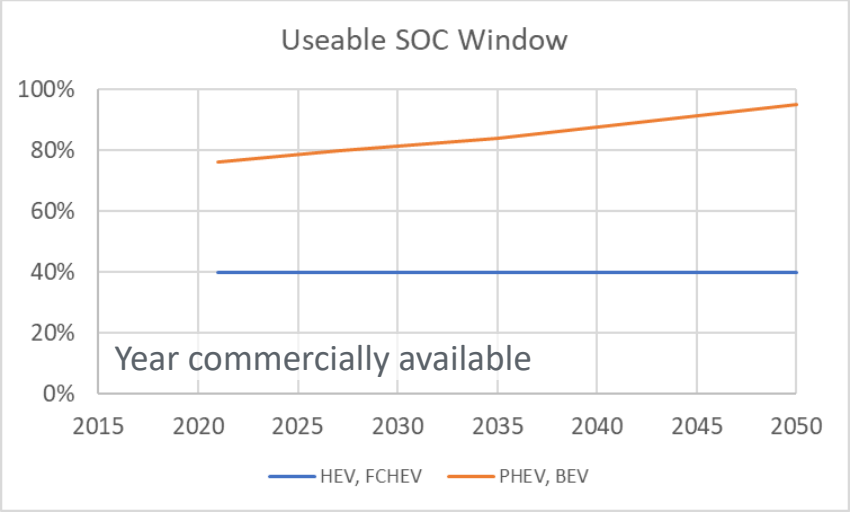
FY 2020 Program Success Inputs: Diesel Engine Peak Efficiency

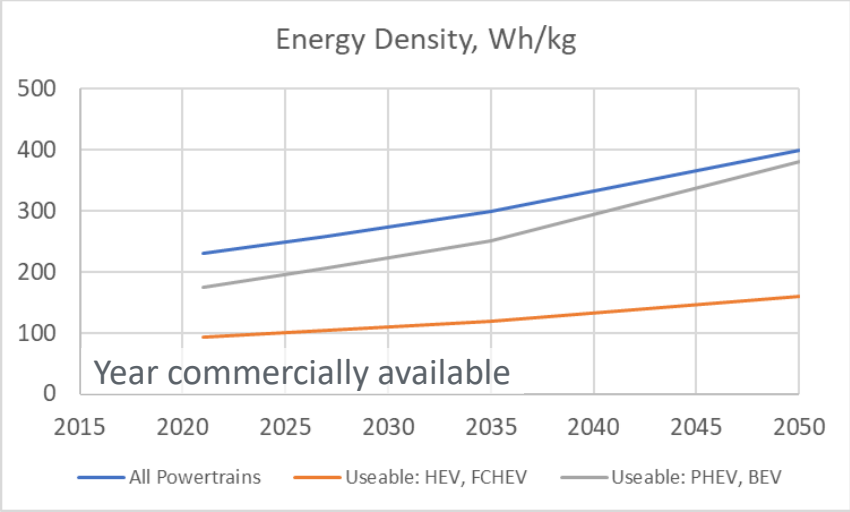


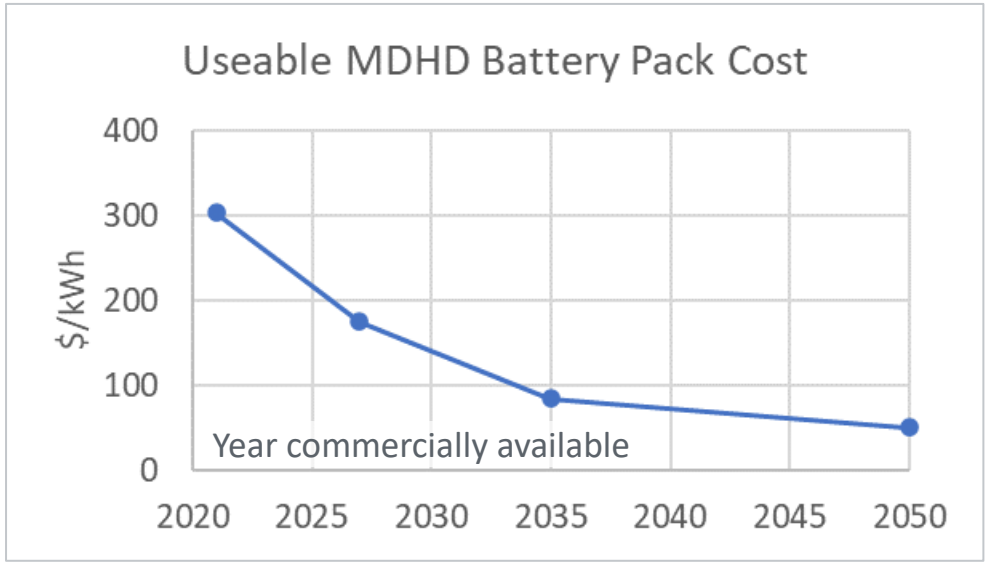


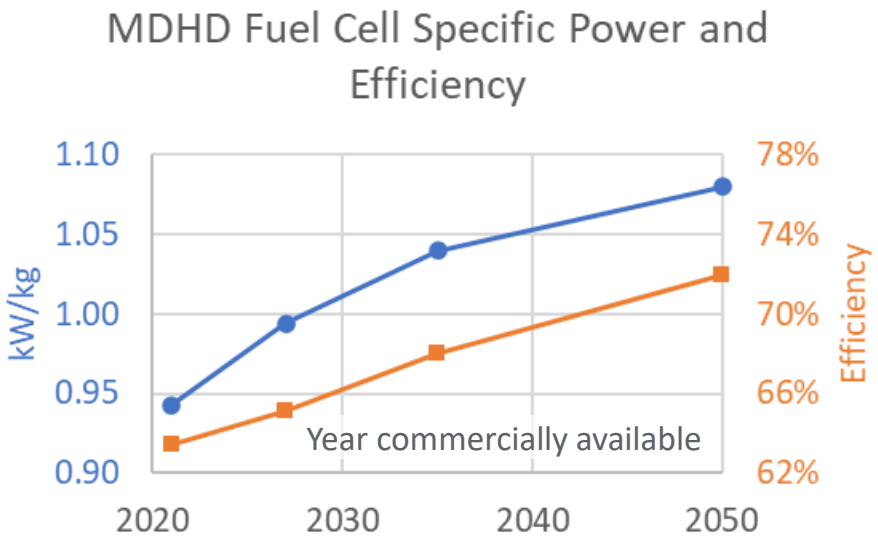
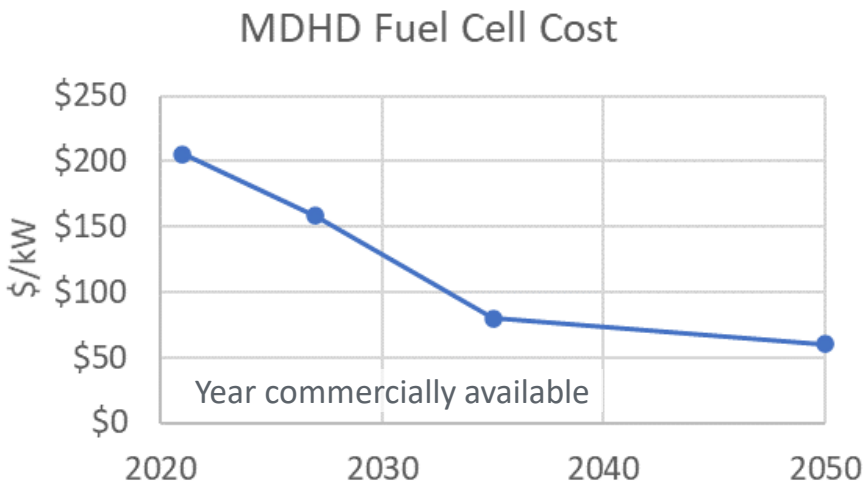
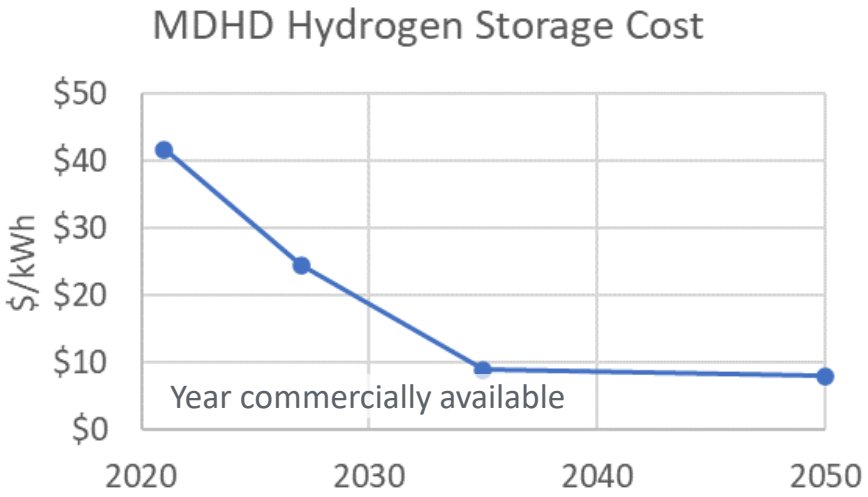
- Cost includes engine, waste heat recover (tractors) and transmission
- Additional cost for idle reduction (stop-start, engine shut-down) added to vocational vehicles

FY 2020 Program Success Inputs: Energy Storage







- Battery sized with 10% safety factor on range requirement (e.g., if range requirement = 500 miles, size for 550 miles)
- Useable energy density based on useable SOC window
- Vehicle mass includes additional 20% mass for other components (mass compounding factor of 1.2)
- Battery price = 1.5 x Cost

FY 2020 Program Success Inputs: Hydrogen Fuel Cell